The PDS-XADS Reference Accelerator

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At the start-up of the PDS-XADS project, the main initial specifications for the accelerator system (e.g. beam energy, beam intensity, beam profile, their stability and the accelerator availability and reliability) have been defined by Working Package 1 (WP1), in connection with the other WP of the project. From this, WP3 ("The Accelerator") has assessed the main requirements and the corresponding technical answers. A reference solution, based on a linear superconducting accelerator with its associated doubly achromatic beam line has been worked out up to some detail. For high reliability, the proposed design is intrinsically fault tolerant, relying on highly modular "de-rated" components associated to a fast digital feedback system. The proposed solution also appears to be robust concerning operational aspects like maintenance and radioprotection. A program for the remaining required R&D has been elaborated.

1. Introduction

Consecutive to the work [1] of the European Technical Working Group (ETWG) on Accelerator Driven Systems (ADS), the Preliminary Design Study of an Experimental ADS (PDS-XADS) was launched in 2001. A large European Collaboration, supported by the EU within the 5th Framework Programme, performs these studies [2]. Five Working Packages (WP) cover the relevant issues, where WP3 is dedicated to the design of the high intensity proton accelerator for an XADS.

Coordinated by CNRS-IN2P3, the following institutions collaborate on the elaboration of the six deliverables of WP3: ANSALDO (Italy), CEA (France), CNRS-IN2P3 (France), ENEA (Italy), Framatome ANP (France), Framatome GmbH (Germany), FZ Jülich (Germany), IBA (Belgium), INFN (Italy), ITN (Portugal), University of Frankfurt (Germany).

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WP3 contains the following deliverables, where the organization responsible for issuing the document is given in parenthesis:

- Requirements for the XADS accelerator and the technical answers (CEA)
- Potential for reliability improvement and cost optimization of linac and cyclotron accelerators (INFN)
- Accelerator: feedback systems, safety grade shutdown & power limitation (CEA)
- Accelerator: radiation safety and maintenance (CNRS)
- Definition of the XADS-class reference accelerator concept & needed R&D (CNRS)
- Extrapolation from XADS accelerator to the accelerator of an industrial transmuter (INFN)

In order to accomplish the tasks to be performed within these deliverables, WP3 naturally relies on input from the other working packages and conversely provides output to them. On the technical interfacing aspects, a good interaction is established with the other WP concerned with the design of the main components (and their principal versions) of the XADS. Further, a particular rôle is played by the link with WP1 guaranteeing the overall coherence of PDS-XADS. Today, slightly past mid-term of the contract, the studies of WP3 are already in a quite advanced phase (e.g. certain deliverables are released in final form), and the following sections of this paper aim at giving a synthetic view of the facts and findings.

2. XADS Accelerator Specifications

The main technical specifications for the XADS accelerator are summarized in Table 1. These characteristics clearly show that this machine belongs to the category of the so-called HPPA (high-power proton accelerators). HPPA are presently very actively studied (or even under construction) for a rather broad use in fundamental or applied science [3]. The overall performance of the sub-critical system will be critically determined by a strict adherence of the XADS accelerator to its specifications. Compared to other HPPA, many requirements are similar, but it is to be noted that the reliability specification, i.e. the number of unwanted "beam-trips", is rather specific to the use as driver for an ADS. Therefore, the WP3 studies for the reference design had to integrate this stringent requirement from the very beginning, taking into account that this issue could be a potential "show-stopper" for ADS technology in general.

Table 1. XADS proton beam specifications.

Max. beam intensity	*6 mA CW on target (10 mA rated)*
Proton energy	*600 MeV (includes 800 MeV upgrade study)*
Beam entry	*Vertically from above preferred*
Beam trip number	*Less than 5 per year (exceeding 1 second)*
Beam stability	*Energy: ±1 %, Intensity: ±2 %, Size: ±10 %*
Beam footprint on target	*Gas-cooled XADS: circular ∅160* *LBE-cooled XADS: rectangular 10×80* *MYRRHA: circular, "donut" ∅72*
Intensity modulation	*0.2ms "holes" in CW beam for neutronis measurements, repetition frequency 0.01-1 Hz*

3. Choice of the basic accelerator concept

With the present state-of-the-art in accelerator technology, only two basic concepts of accelerators have shown to be able to deliver beam intensities in the mA range. These namely are sector-focused cyclotrons and linear accelerators (linacs).

Concerning cyclotrons, a final energy of 600 MeV is well established [4], namely with the experience of the PSI machine, and from this, it is felt in the cyclotron community, that a value of about 5 mA should be considered as safely reachable. However, extrapolating up to 10 mA is more questionable, and might require a complex of at least two cyclotrons with the two beams being funneled together. A (given) cyclotron also cannot be expanded in energy, so that boosting the energy from 600 to 800 MeV, as envisaged by WP1 would require the full replacement of the final and main stage, an absolutely not cost effective operation. For energies of in the GeV range (industrial transmuter), the intrinsic limits of the very working principle of a cyclotron is reached, because the proton becoming too relativistic. Furthermore, a cyclotron is basically a CW machine and the requirement to provide pulses for neutronics measurements is a major difficulty for a cyclotron of such power. None of all these limitations† are present in a linac where intensities can reach above 100 mA without an intrinsic energy limit.

As will be further discussed in the next sections, the strategy to implement reliability relies on over-design, redundancy and fault-tolerance [5]. This approach requires a highly modular system where the individual components are operated substantially below their performance limit. A superconducting linac, with its many repetitive accelerating sections grouped in "cryomodules", conceptually meets this reliability strategy. It further allows keeping the activation of the structures rather low, important for radioprotection and maintenance issues, whereas the extraction channel of high power cyclotrons is in this respect a considerable concern.

For all these reasons, WP3 concluded that the cyclotron solution for an XADS presents a number of difficulties if not impossibilities: funneling, pulsing, beam trips, double-machine scheme, intrinsic current limitation, energy upgrading that precludes this solution despite its advantages such as lower price, proven technology at the MW level as demonstrated by PSI, and compactness. Therefore, the reference solution discussed in the next section is a superconducting linac [6].

Finally, it should be noted this assessment is corroborated by the one of OECD/NEA [7]:

Cyclotrons of the PSI type should be considered as the natural and cost-effective choice for preliminary low power experiments, where availability and reliability requirements are less stringent. CW linear accelerators must be chosen for demonstrators and full-scale plants, because of their potentiality, once properly designed, in term of availability, reliability and power upgrading capability.

4. The XADS accelerator reference layout

4.1. *A reliable linac*

The proposed reference design for the XADS accelerator, optimized for reliability, is shown in Figure 1. It is composed of a "classical" proton injector (ECR source + normal conducting RFQ structure). Additional warm IH-DTL or/and superconducting CH-DTL structures are used up to a transition energy. At

† The released deliverables D9 and D57 elaborate these schematic considerations up to a certain level of detail

this point a fully modular superconducting linac accelerates the beam up to the final energy.

Up to the transition energy, fault-tolerance is guaranteed by means of a "hot stand-by" spare. Above this energy, "spoke" and, from 100 MeV on, "elliptical" cavities are used. Beam dynamic calculations for this part have shown that an individual cavity failure can be handled at all stages without loss of the beam[‡]. Besides this fault-tolerance, another remarkable feature of the concept is its validity for a very different output energy range: 350 MeV for the smaller-scale XADS require 9 cryomodules of β=0.65 elliptical cavities; in order to obtain 600 MeV, simply 10 more cryomodules have to be added (7 with β=0.65 and 3 with β=0.85) and 12 additional (β=0.85) boost the energy to 1 GeV. Therefore, already the small-scale XADS accelerator is fully demonstrative not only of the 600 MeV XADS (and could be converted to it), but even for an industrial machine.

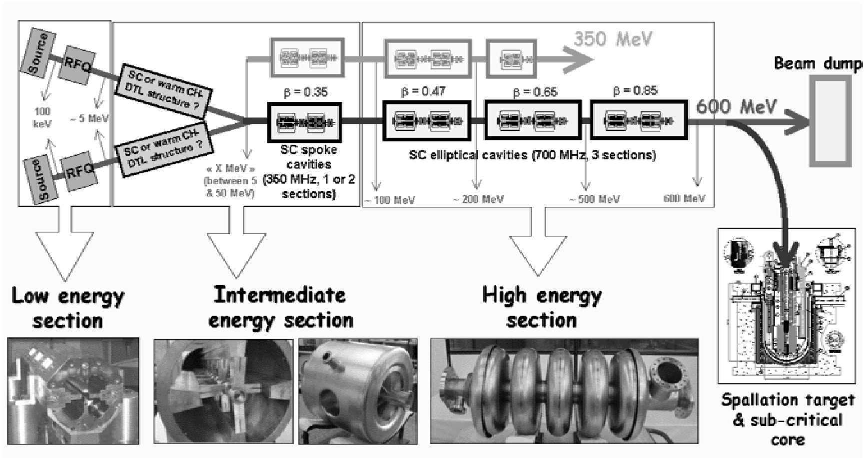

Figure 1. XADS reference accelerator layout: a doubled injector accelerator is followed by a fully modular spoke and elliptical cavity superconducting linac. Photos of typical cavity prototypes are shown in the lower part. From left to right: RFQ, CH structure, Spoke, Elliptical 5-cell.

The chosen superconducting cavities are subject of important R&D programmes presently underway, e.g. at the laboratories of the collaborating institutions of WP3. The performance of the prototypes has been measured to exceed the operational characteristics for the XADS by a very comfortable safety

[‡] Calculations accomplished within PDS-XADS deliverable D57 (INFN & CNRS-IN2P3)

margin [8] that ensures the "over-design" criteria imposed by the reliability strategy.

4.2. *A safe beam transport line*

The objective of the final transport line is to safely inject the 600 MeV (or 350 MeV) proton beam onto the spallation target with a footprint of the required size and density distribution.

To this end, a doubly achromatic module composed of two 45 degrees bending dipoles and three focusing quadrupoles has been designed[§] and adopted for the two reference XADS concepts. With scaled magnetic rigidity, the same layout can be used at 350 MeV. Such a system is non-dispersive. Therefore, the beam position at the target does not depend on the energy variations, and, in addition, the beam size is independent of the internal beam energy spread. Thus, residual energy spread and central energy fluctuations from the accelerator will have no effect on the beam stability at the target.

The system is however dispersive in the region situated between the two dipoles. Thus, the beam position and beam size monitors located in this region will be able to provide information on proton energy variations, and to trigger a feedback system.

To expand the beam onto the target, the so-called raster scanning method has been adopted. It consists in deflecting a pencil-like beam with fast steering magnets operated at frequencies of 50 to a few hundreds Hertz, and acting in the two transverse directions in order to paint the target area. Various shapes (rectangular, circular) and various particle distributions (uniform, parabolic…) are achievable by simply adjusting the rastering frequencies of the steerers.

The scanning system would be very similar (but less demanding) to the one studied for the APT and ATW projects. Four raster magnets will be operated synchronously and independently so that the beam will be always moved at the target if one magnet fails. Redundant fault detection circuits will monitor the magnet current and the magnetic field to ensure proper operation and to shut down the beam in case of necessity. Similar systems are used in cancer therapy with protons or heavy-ion where they meet the stringent requirements for medical use[**].

[§] Details are given in deliverable 9

[**] e.g. WP3 participant IBA has such systems developed commercially

4.3. *A shielding for radiation protection*

The shielding calculations for the XADS accelerator must be in line with the general radiation protection philosophy, based on the recommendations from the ICRP publication n°60 [9] that have been adopted in the European decree Euratom/96/29; all national legislations of the member states of the European Union must respect this European decree.

The goal of the shielding design of the XADS accelerator is therefore to guarantee that, under normal operational conditions, the added integrated dose to anybody working around the XADS accelerator will be extremely small, i.e. comparable or smaller than the natural background. To obtain this goal, the shielding calculations are made using conservative (= pessimistic) normal beam loss assumptions, and assuming an "occupancy factor" of 1, that means that a person will be present during 2000 hours per year immediately behind the shield wall where maximum dose rates exist. The design dose rate is 0.5 μSv/h, corresponding to the ICRP-60 annual limit of 1 mSv for the public, taking into account an annual working time of 2000 hours. The natural background being of the order of 1mSv/y, the conservatism built into the shielding calculations should therefore guarantee that the effective dose for any person resulting from the operation of XADS accelerator will be smaller than the natural background. This is an important argument because it is not unlikely that future ICRP recommendations will go in the sense of comparing exposure from "man-made" sources to exposure from natural sources.

The shielding defined for the normal operational conditions, with the conservative criteria explained above, must also guarantee that extra exposure to radiation created from abnormal operational conditions must remain sufficiently low, in order not to jeopardize the main shielding objective, i.e. keep the total integrated dose added by the operation of the XADS accelerator, for any person, below the natural background. The exposure to radiation from activated accelerator components is minimized via a system of administrative measures, by keeping the normal beam losses in the accelerator small and keeping the integrated power of accidental beam losses as low as possible via a powerful accelerator interlock system.

Figure 2 shows, e.g., the required earth profile in the case of an accelerator tunnel with 60 cm (light-concrete) side walls and roof, buried underground (the top of the concrete roof corresponds to zero ground level). The profiles correspond to the minimum earth thickness required to reduce the residual dose levels outside the earth below 0.5 μSv/h for a 1 nA/m linear beam loss at 350 MeV (MYRRHA case). For higher energies, it will be sufficient to slightly increase the amount of earth[††] It is remarkable that the shielding profiles derived from the requirements for normal operation will provide sufficient shielding for the planned commissioning period as well as for planned periods of beam tuning and setup, by allowing beam loss rates 100 times higher than during normal operation during significant periods of time, and it will also protect correctly against several types of accident condition.

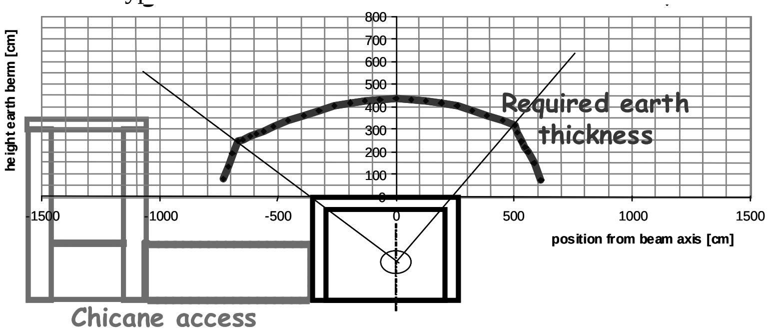

Figure 2. Required earth profile above the 60 cm thick concrete linac tunnel, for at 350 MeV proton energy and 1 nA/m linear beam losses. An access to the linac tunnel (chicane) is also shown.

4.4. *A maintenance strategy*

The foremost goal of the maintenance strategy for the XADS accelerator is to guarantee its reliability and availability goals for its operation[‡‡], and that for its anticipated period of life, i.e. an order of magnitude of 30 years.

In other words, proper maintenance has to guarantee that the “over-design” margin does not deteriorate and that a proper amount of redundant equipment is regularly restored if partial failures have occurred. Concerning fault-tolerance, there again, lost equipment has to be replaced at a regular basis, and it is of prime importance to ensure that the supervising control system regularly undergoes a complete performance check to ensure that it can replace components-at-fault by readjusting the operational parameters of the overall machine.

These requirements request the development of an expert system able, while the accelerator is running and delivering nominal beam, to precisely identify and locate equipment that has started to loose rated performance, and/or that is out-

[††] Calculations performed within deliverable D48 by Paul Berkvens and Serge Palanque
[‡‡] WP3 presently uses as reference an operational scheme of 3 month of uninterrupted beam, followed by a 1 month maintenance period.

of-order and to be replaced or repaired. Thus, the expert system provides the database that will be used during the scheduled maintenance periods for planning repair and/or replacement of deteriorated or faulty equipment.

This fastest possible way of preparing the maintenance procedure also is in-line with the ALARA[§§] principle for the concerned personnel. Indeed, one may point out that many conditions requested for radiation doses conforming to the ALARA principle, like enough working place and quick disconnection of sub equipments are actually the very much the same that are asked by an optimization of the reliability.

5. An R&D programme focused on reliability

5.1. *Generalities*

As already mentionned in section 2, the broad field of applications covered by HPPA accelerators is at the origin of remarkable R&D effort presently underway world-wide. The study, design and testing of the main components of these new generation linear accelerators have contributed to a good synergy by developing complementary activities between many laboratories (see also [8] and references therein).

Table 2. Summary of the R&D topics needed for the XADS accelerator, including the responsibilities of participating laboratories, and an estimate of the necessary EU contribution.

	Low Energy Section	Intermediate Energy Section				High Energy Section	RF System	Global Coherence
R&D Topic	Injector Reliability	Spoke cav. (SC)	CH struct. (SC)	IH struct. (NC)	Other cav. (SC)	Beta 0.5 Cryomodule	Control System	
Responsible	CEA	CNRS				INFN	CEA	CNRS
Participants	CNRS, INFN, U.Fra	CEA, FZJ, IBA, INFN, Framatome-CERCA, U.Fra				CEA, CNRS, IBA	IBA, INFN, ITN	CEA, ENEA, IBA, INFN, ITN, U.Fra
Requested EU Contribution	1 M€	2 M€				2.5 M€	0.5 M€	0.5 M€

The XADS accelerator can profit from these general background and even built on it quite directly. However, a dedicated R&D programme has to be proposed in order to guarantee the requirement for the extremely low number of beam trips. It has to be focused on reliability and fault tolerance design. In this spirit, participant laboratories to WP3 have developped during the last month a

[§§] ALARA: As Low As Reasonably Achievable.

collaborative R&D program that could be submitted within the forthcoming 6^{th} FP call (cf. Table 2).

5.2. *Specific Issues for the injector*

Concerning the injector section, its feasibility has already been demonstrated in the frame of several projects either partly, like in the IPHI (France) and TRASCO (Italy) projects, or completely, like in the LEDA project (Los Alamos, USA). But the high reliability required by the XADS accelerator implies to start a thorough campaign to test the reliability of every component of the injector, operated over a long period of time (a continuous run of 6 months for example) at very high power, which would require additional resources from FP6.

5.3. *Specific Issues up to 100 MeV*

Some basic R&D is required for the subsequent sections, up to 100 MeV, in order to assess a solution simultaneously reliable and economical. For these reasons, WP3 has developed the vision that superconducting components should in principle be used "early on".

However, "the warm option" has to be carefully studied and prototyped for two reasons. First, it could very well be required for boosting the RFQ-injector energy if the transition energy to the superconducting structures is higher than the RFQ output. Second, although the RF losses are quite high for the warm option, its development risk is low, relying on a well established technology. In fact, the warm option could as well be considered a baseline option to which the new superconducting structures have to be compared with. Indeed, the superconducting resonators considered within WP3 are short and modular. That enables a better and more efficient approach for the implementation of the reliability strategy. First cavity prototypes for the intermediate section are presently built and tested with quite a success [8]. It is therefore important to actively pursue these developments, in particular for spoke- and CH- structures equipped with their helium tank and power coupler in order to built a complete cryomodule. The final aim of all these developments would be to asses the best technical option for the intermediate section of the XADS accelerator based on established demonstrated performance.

At present, several participating institutions to WP3 (from Belgium, France, Germany and Italy) are already engaged in these R&D tasks using their own funding resources. If the dead-line of 2006 for the decision on an XADS accelerator is to be met the present yearly funding is to be maintained and to be complemented by FP6 resources.

5.4. *Specific issues at high energy*

Concerning the high-energy section, R&D is already going on since a few years in Europe on superconducting elliptical cavities at a frequency of 700 MHz. Nevertheless, the demonstration of the full technology is not yet accomplished, and needs a few more years of additional work. As a matter of fact, it is important, besides the development of the bare superconducting cavity, to build prototypes of each auxiliary system needed for the cavity operation in a real environment (power coupler, RF source, power supply, RF control system, cryogenic system, cryostat…). This full demonstration requires the construction of a real prototype of an accelerating module in which, in addition to the superconducting cavities, all these elements have been included. The construction of such an integrated module at a given beta value (for example β = 0.5) would thus be considered as a proof of principle of the technology, not only for that particular beta, but also for all others since many similarities exist between them. Moreover, such a module could allow real scale demonstration with RF tests at nominal power (although without beam), and could be used for specific studies dealing with the XADS reliability issue, like the completion of the RF control system procedures in case of a cavity failure.

5.5. *R&D for an RF system*

Finally, the last item concerns the study and development of the RF system referred to in section 5.4 of which the low-level part needs to be highly specialized for an XADS accelerator. This system must handle beam trips, reacting with enough speed to retune the whole accelerator, in order to recover nominal beam conditions in a short time (less than 1 second) and to ensure the fault-tolerance principle. Digital techniques are necessary to meet the speed and software configuration requirements. Unique specialized control software and adapted interfaces to the RF power electronics systems must be also developed and tested. Co-funding by FP6 resources would allow to start this essential programme.

6. Concluding Remark

Within a period of less than two years, it has been possible to develop a generic and robust technical solution for the XADS accelerator and its associated beam-line. This solution, based on a superconducting linear accelerator, can fulfill a priori the specifications for the XADS. This linac can be used for all different versions of XADS studied within the 5th FP, and it is also representative for an industrial machine.

The proposed machine is reliable through the rigorous implementation of a highly modular system with de-rated components operated in a fault-tolerant way. The continuation of the vigorous R&D programme presently underway, with a focus on the reliability aspect within the 6th FP, places the XADS accelerator on a roadmap in-line with the TWG recommendations.

Acknowledgments

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